The Reflecting Power of the Alkali Metals

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN PHYSICS IN THE GRADUATE SCHOOL OF THE UNIVERSITY OF ILLINOIS

BY

JONAS BERNARD NATHANSON

A.B. Ohio State University, 1912

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THE REFLECTING POWER OF THE ALKALI METALS

By J. B. NATHANSON

I. INTRODUCTION

The alkali metals, by virtue of their great chemical activity and their interesting electrical and optical properties, afford interesting fields for research. The great difficulty in handling the metals has, however, limited their investigation. Further interest in these metals has been added by the comparatively recent study of the selective photo-electric effect which, it has been suggested, might be due to the peculiar optical properties of the alkali metals in the region of the selective effect. If such be the case, there ought to be a marked change in the reflecting powers of the alkali metals in this region. Consequently any knowledge of the reflecting powers of the alkali metals as a function of the wave-length and plane of polarization is highly desirable, and it is to this end that the present investigation has been carried out.

Up to the present no direct method has been employed in the study of the reflecting powers of the alkali metals. All our knowledge rests upon the comparatively few katopric measurements. The first investigation was made by Paul Drude[1] upon the single metal sodium. The reflecting surface was formed by melting the

[1] *Annalen der Physik*, 64, 159, 1898.

sodium in a vacuum, and the reflecting power obtained from a study of the nature of the reflected elliptically polarized light.

In 1913, R. W. and R. C. Duncan[1] made a more extended investigation of the optical properties of sodium and potassium as a function of the wave-length. Drude's method was employed. The metals were used in the form of mirrors, i.e., glass backed by metal. These authors found very high values for the reflecting powers of sodium and potassium, the former being the better of the two.

In the present investigation the reflecting powers have been obtained by a direct measurement of the incident and reflected light-intensities. A photo-electric cell was used as a photometer, the cell being previously calibrated in terms of known light-intensities. This use of the photo-electric cell has been anticipated by E. V. Hulburt,[2] whose work appeared during the progress of this investigation. Hulburt determined the reflecting powers of a large number of metals for ultra-violet light, the angle of incidence being kept constant. It appears that Hulburt assumed a linear relation between the photo-electric current and the light-intensity, an assumption which does not seem to be justified in view of this and other investigations.

II. WHITE, UNPOLARIZED LIGHT: RELATION BETWEEN THE PHOTO-ELECTRIC CURRENT AND THE LIGHT-INTENSITY

The apparatus.—In the present investigation of the reflecting power of the alkali metals, a photo-electric cell was employed as a photometer. The cell chosen was one of the most sensitive ones made by Dr. Jakob Kunz of this Laboratory. The cathode consisted of rubidium deposited by distillation upon a film of silver. The anode consisted of a loop of platinum wire. Between the anode and cathode is located a platinum guard ring which is usually earthed to avoid leakage across the glass between the electrodes.

Investigations on the relation between the photo-electric current and the light-intensity are not in good agreement with each other. While Elster and Geitel[3] and Richtmeyer[4] have shown

[1] *Physical Review*, **36**, 294, 1913.

[2] *Astrophysical Journal*, **42**, 205, 1915.

[3] *Annalen der Physik*, **48**, 625, 1893.

[4] *Physical Review*, **29**, 71 and 404, 1909.

that the photo-electric current is strictly proportional to the light-intensity, on the other hand Lenard[1] and quite recently Ives[2] have shown that the linear relationship does not strictly hold. Ives, in an extended investigation of the subject, wherein he subjected a great variety of cells to different conditions, showed that the relation is not a linear one, but that the photo-electric current is a complicated function of the voltage, electrode distance, and gas pressure in a cell.

Consequently, owing to the conflicting literature on this subject, it was decided, before using the cell above as a photometer, first to calibrate it in terms of known light-intensities by the aid of crossed nicol prisms. To this end, the arrangement of apparatus shown in Fig. 1 was employed.

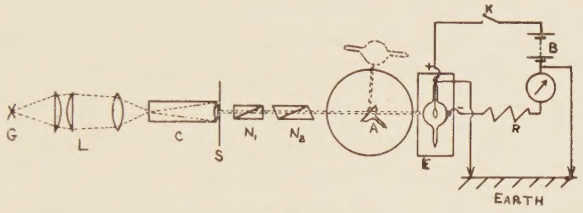

FIG. 1

A Nernst glower G was used as a source of light, both on account of its intensity and because of its reputation for constancy. The light after passing through several condensing lenses L is focused upon the circular aperture of the collimator lens. The light then passes through the nicols N_1 and N_2, the former having rectangular ends to eliminate rotation of the beam when N_1 is rotated.

The circular beam of parallel rays of light is then incident upon the photo-electric cell, which is inclosed in the earthed metallic box E. This box was air- and light-tight, and blackened on the inside. It served to eliminate any possible extraneous light. In this box was placed some phosphorous pentoxide to render the air dry and so to diminish leakage across the glass or across the hard rubber disks through which were conducted the wires leading to the electrodes of the cell. The beam was admitted through a glass

[1] *Annalen der Physik*, 8, 149, 1902.

[2] *Astrophysical Journal*, **39**, 428, 1914; **43**, 9, 1916.

window, before which was placed a shutter sliding on a groove, so that by means of a cord and pulleys the shutter could be easily raised or lowered by the observer at his observing station.

The voltage used across the photo-electric cell varied from 111 to 134 volts, this being furnished by a set of constant potential cells. As a detector of the photo-electric current, a sensitive galvanometer was employed, being loaned to the writer by the Department of Astronomy through the kindness of Professor Joel Stebbins. This galvanometer had a figure of merit of 5×10^{-10}. The terminal of the galvanometer next to the negative pole of the battery was earthed. This was found to be highly essential, serving to eliminate completely troublesome leakage currents in the circuit, and enabling one to take observations with the greatest accuracy in the most humid days of the summer.

Method of observation.—With the axes of the nicols parallel to each other, the cell was exposed to the light and the galvanometer deflection observed. Then the deflection was observed for some angle between the nicols. Finally, the nicols were made parallel again, and the deflection again observed. This last observation served as a check on any fluctuations of the light-intensity that might have occurred during the observations. As a matter of fact, the light-intensity was absolutely constant only on rare occasions, there being usually a small and slow variation. However, by continual checking of the deflection for zero angle between the nicols, proper corrections could be applied to the deflection for any angle between the nicols.

Several readings were always taken for each position of the nicols. The individual readings usually agreed to within two- or three-tenths of a millimeter for the larger deflections, and to a correspondingly smaller extent for the smaller deflections.

The results.—In Fig. 2 are given the deflections corresponding to various light-intensities, the latter being proportional to the squares of the cosines of the angles between the two nicols. Each deflection is the average of two to four observations.

Upon examination of the plotted results, it is evident that the current light-intensity relation is *not* a strictly linear one, but is in the form of a curve slightly concave toward the illumination-

axis. The results for the curve labeled 130 volts were obtained by using a different quadrant of the nicol prism, N_1; the light

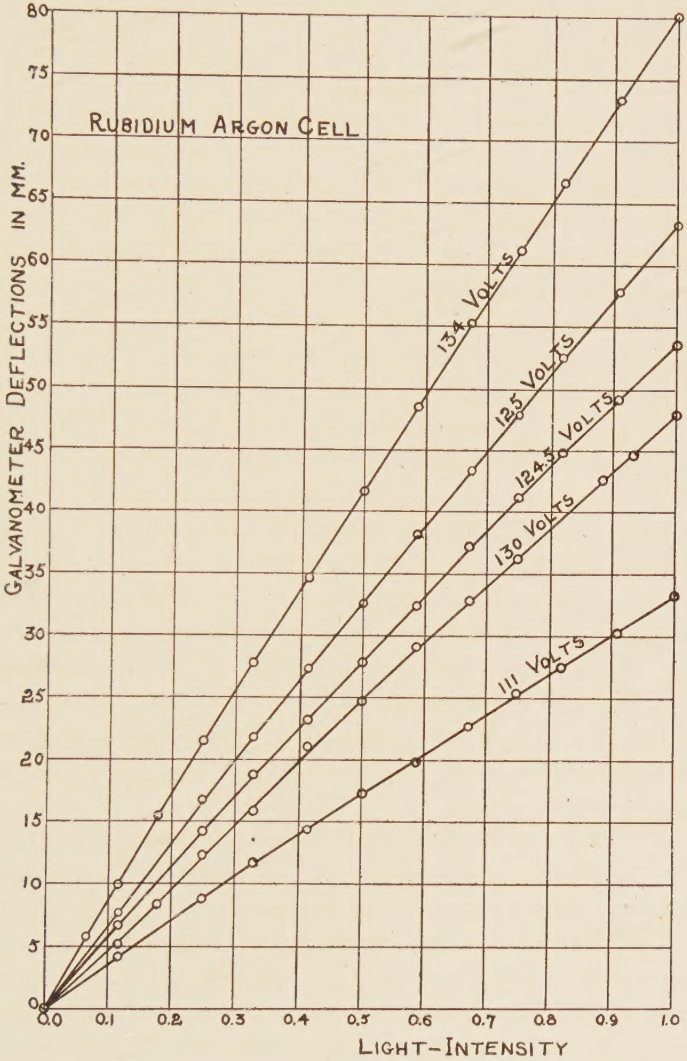

FIG. 2

also was somewhat weaker than in the other three cases, whence the smaller deflections. This serves to show that the concavity of the curves cannot be due to lack of symmetry of the nicol prism. This

concavity increases, the larger the range of the deflections. In the succeeding determinations of reflecting powers, proper corrections were always made in accordance with these curves.

III. PREPARATION OF THE ALKALI MIRRORS

The alkali mirrors were made either by distillation or by pouring the metal upon a square piece of plane glass about 2.5 cm on edge and 1.74 mm thick. The cell *C* was made by joining a small piece of glass tubing to a much wider piece. The latter was then cut off, leaving a bell-shaped opening. The edge of this bell was ground plane with emery and finally with rouge, the edge becoming highly polished. The glass plate, after being thoroughly cleaned with alcohol, potash, and nitric acid, was then clamped tightly against the polished edge of the bell, and "Rock Cement" applied thickly around the edge *P*. The bell was then placed in an electric oven, and baked at about 140°C. Usually three applications of cement were applied to the cell. The baking was continued until the cement turned to a brownish color. This cement served excellently in making the cell air-tight, and in enabling one to subject the cell to much heat during the distillation of the metal, without endangering the vacuum.

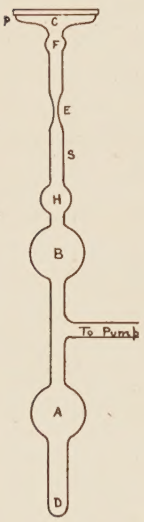

FIG. 3

The cell was then attached to the glass apparatus shown in Fig. 3. In the case of Na and K, the metal was introduced into *A* through *D*, which was then sealed off, and the tube evacuated. The metal was then melted down with an electric coil. Great care is necessary in this process, as the glass is likely to crack very easily when the molten metal bursts out of its oxide skin.

A portion of the metal was poured into *B*, and from there distilled to *H*. A small molten globule was then guided to the concavity *F*. In this process the tube was removed from the pump, and the globule guided to *F* by means of successive jars by the hand. The metal was then distilled against the glass plate which was placed in contact with a flat piece of ice. The metallic vapor thus deposited itself upon the plate in the form of a mirror,

the layer of metal being made thick enough to be entirely opaque to light. The mirror was then sealed off and removed at *E*.

In the case of one of the K mirrors (mirror No. 2), a large amount of the metal was collected in *H* by distillation, and the whole molten mass forced into the cell against the glass plate, making a mirror out of a solid cake of the metal.

Rubidium cannot be obtained on the market in metallic form, and so had to be obtained by reducing RbCl with Ca, the materials being placed in an iron boat inclosed in a hard glass tube attached to *D* of Fig. 3. The metallic vapor was condensed in *A* before it was redistilled and deposited upon the glass plate.

Success in making the mirrors was not always attainable, there being many opportunities for failure in the long process. Many of the mirrors after being formed were found to have thin oxide films on their surfaces, and so were discarded. Only those mirrors were picked for investigation which appeared perfect as viewed by the eye.

IV. ARRANGEMENT OF APPARATUS FOR THE DETERMINATION OF THE REFLECTING POWER

In the determination of reflecting powers the arrangement of apparatus shown in Fig. 1 was employed, the nicol prisms being, however, removed so that the light incident on the mirrors was unpolarized. The metallic box containing the photoelectric cell was mounted upon the telescope arm of the spectrometer to facilitate the movement of the cell for any angle of incidence desired.

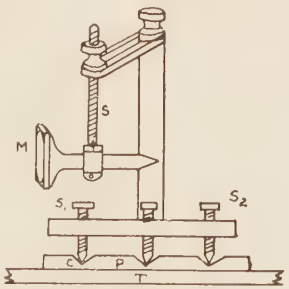

FIG. 4

The mirror *M*, Fig. 4, was mounted on a small tripod, whose legs fitted into cups *C* on a brass plate *P* which could be permanently clamped to the top of the spectrometer table *T*. The center of the reflecting face of the mirror was adjusted to lie along the axis of the spectrometer. After proper adjustment the plate *P* was clamped to the table *T*. By this means the mirror could be removed from the spectrometer table and quickly replaced in its original position.

This was found desirable, since, in the determination of reflecting powers, observations on the unreflected beam were alternated with observations on the reflected beam. Using this method of observation proper corrections could be made in case the light-intensity, or voltage across the photo-electric cell did not remain absolutely constant.

V. THE FORMULA

The ratio of the reflected light-intensity to the incident light-intensity gives the reflecting power of the whole mirror, i.e., metal plus glass. The greater interest lies in the reflecting power of the metal itself when in contact with the glass. Knowing this, it is possible to form a very close approximation as to what the reflecting powers of the metals would be in a vacuum.

Owing to the large number of internal reflections, the following mode of reasoning will be used to determine the reflecting power of the metal. Let

I = the light-intensity of the incident light
i = angle of incidence
r = reflecting power of the front face of the glass, i.e., the fraction of the incident light, incident on the glass, which is reflected back into the air
r' = reflecting power of the interior glass surface, i.e., for light internally reflected, e.g., as at C, E, and G
t = transmission power of the glass plate for a given thickness, i.e., the fraction of the light which, e.g., after penetrating the surface at A, reached the point B
R = reflecting power of the alkali metal, i.e., the fraction of the light incident on the metal glass boundary at B, for example, which is reflected by the metal.

The quantities r, r', t, and R are functions of the angle of incidence.

The sum of the components of reflected light-intensities, a, b, c, d, etc., are given by the series

$$O' = Ir + I(1-r)(1-r')t^2R(1+r't^2R+r'^2t^4R^2+r'^3t^6R^3+ \ldots .).$$

The photo-electric cell registers the sum of all these components of the reflected light-intensity. If $O=\frac{O'}{I}$ is the reflecting power of the whole mirror (metal plus glass), then

$$O=r+\frac{(1-r)(1-r')t^2R}{1-r'Rt^2}.$$

Hence

$$R=\frac{O-r}{t^2(1+Or'-r-r')}. \qquad (1)$$

This is the formula that was employed in the determination of the reflecting power of the alkali metals. It will be noted that in order to know R the optical properties of the glass plates used in these mirrors must be determined.

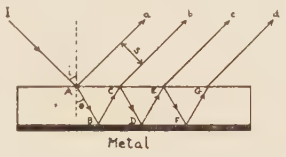

FIG. 5

Inspection of Fig. 5 shows that the beam after reflection is spread out. If S is the lateral displacement between two successive components, then applying Snell's law it follows that

$$S=\frac{t\sin 2i}{\sqrt{n^2-\sin^2 i}} \qquad (2)$$

where t = thickness of the glass = 1.74 mm
i = angle of incidence
n = 1.5155 = index of refraction

This was determined by means of the Abbe refractometer, using the method of grazing incidence.

Taking i as 60°, the value of S is 1.26 mm. Theoretically, an infinite number of internal reflections occur between the metal and the air-glass boundary. Practically, the components of the reflected beam after the fourth one are negligible. Hence, taking four components as effective, the displacement would be about 5 mm. Adding 3 mm for the width of the beam, the breadth of the reflected beam does not exceed 8 mm. The aperture to the photo-electric cell was almost 2 cm, hence all effective components of the reflected beam were certainly able to enter the cell.

VI. OPTICAL PROPERTIES OF THE GLASS PLATES

In order to determine r, the reflecting power of the front face of the glass plate, the back face was abraided with coarse emery and then coated with lamp-black. The results are shown in Fig. 7, where the continuous line represents the experimental values, while the dotted line gives the theoretical values as given by Fresnel's reflection equation for natural white light.

The experimental values, which at first are smaller than the theoretical values, are, however, larger than the latter for larger angles of incidence. This may be due to a possible slight specular reflection of the abraided rear surface which becomes more effective for the larger angles of incidence. In general, the agreement is quite satisfactory, and demonstrates the adaptability of the photo-electric cell as a photometer.

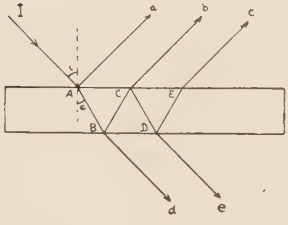

FIG. 6

Determination of t and r'.—The determination of the transmission power and the reflecting power of the internal surface of the glass was effected through a study of the light reflected and transmitted by the glass plate.

Following the method of reasoning employed previously, and adding up the components a, b, c, etc., of the reflected light, we have (see Fig. 6)

$$R'=r+(1-r)(1-r')r't^2+(1-r)(1-r')r'^3t^4+ \ldots . + \ldots .$$

where R' is the reflecting power of the glass plate (both surfaces).

$$R'=r+(1-r)(1-r')r't^2(1+r'^2t^2+r'^4t^4+r'^6t^6+ \ldots .).$$

Hence

$$R'=r+\frac{(1-r)(1-r')r't^2}{1-r'^2t^2}. \qquad (3)$$

Considering the light transmitted by the plate, and summing up the components, d, e, etc., we have for the total fraction, T, of the light transmitted,

$$T=(1-r)(1-r')t(1+r'^2t^2+r'^4t^4+ \ldots .).$$

Hence

$$T=\frac{(1-r)(1-r')t}{1-r'^2t^2}. \tag{4}$$

Combining equations (3) and (4)

$$\frac{R'-r}{T}=r't. \tag{5}$$

Solving for t and substituting in equation (4), and then solving for r',

$$r'=\frac{(R'-r)(1-r)}{T^2+(R'-r)(1-R')} \tag{6}$$

and

$$t=\frac{T^2+(R'-r)(1-R')}{T(1-r)}. \tag{7}$$

Experimentally, R' is obtained by determining the intensity of the reflected light. Keeping conditions the same, T is obtained by merely swinging the cell around on the spectrometer to catch the transmitted light.

The results for R', r', t, and r are plotted in Fig. 7. The values of r' are somewhat lower than those for r, except for values of the angles of incidence approaching the critical angle for the glass plate, when r' crosses r and would ultimately reach 100 per cent for values of the angle of incidence of 41°. It must be borne in mind that the values of the reflecting powers shown in Fig. 7, and in succeeding tables and curves for white light, have been corrected in accordance with the calibration-curves of Fig. 2. By setting up a simple proportion between observed values of the galvanometer-deflections for the unreflected and reflected beam, and values of galvanometer-deflections on the calibration-curves, it has been possible to obtain the corrected values of the reflected light-intensity directly from the calibration-curves. The corrections are of course rather small.

VII. REFLECTING POWERS OF POTASSIUM, SODIUM, AND RUBIDIUM

Three potassium mirrors were investigated. In Table I is given a summary of the results. Mirrors No. 1 and 3 were formed by distillation, while No. 2 was formed by pouring the molten metal

against the glass and allowing it to solidify. The latter method was rendered quite difficult by the tendency of the metal to crystallize upon solidification.

The agreement between the reflecting powers for the different mirrors is indeed quite satisfactory considering that the mirrors

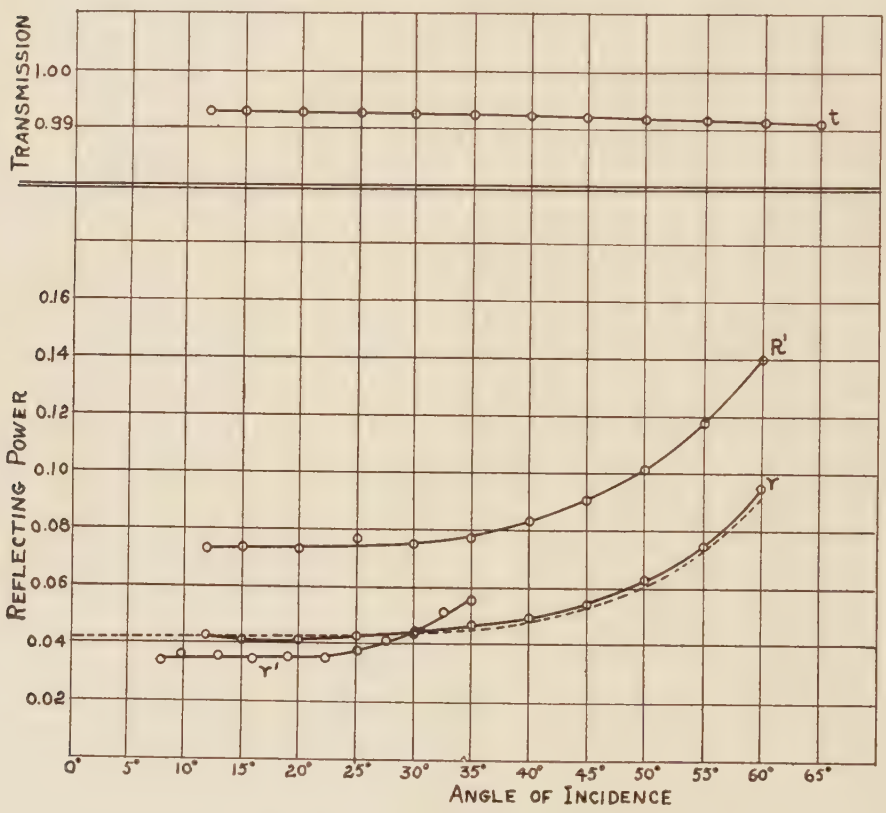

FIG. 7

were made at different times and under different circumstances. Especially is the agreement between mirrors Nos. 1 and 2 to be noted, the former being a distilled mirror, the latter being the "solid" metal mirror. This excludes any doubts that the metallic layers of the distilled mirrors were not thick enough.

The variation of the reflecting power with the angle of incidence is shown in Fig. 8. The reflecting powers increase very slowly

with the angles of incidence. Owing to refraction through the glass plates, the actual angles of incidence on the metal are of course less than those on the whole mirror, so that the curves for

TABLE I

POTASSIUM

O					*R*				
Angle of Incidence	No. 1	No. 2	No. 3	Mean	Angle of Incidence on Metal	No. 1	No. 2	No. 3	Mean
13°5	0.8675	0.869	.....	0.868	8°52′	0.876	0.878	.....	0.877
15	.870	.8685	0.865	.868	9 50	.8805	.8795	0.875	.8785
20	.869	.869	.8645	.8675	13 3	.8805	.8805	.876	.879
25	.8675	.8805	.8685	.872	16 12	.880	.8925	.8805	.8845
30	.888	.873	.875	.8785	19 16	.900	.8845	.887	.8905
35	.8695	.8835	.863	.872	22 14	.8815	.8965	.876	.8845
40	.885	.880	.858	.8745	25 6	.898	.892	.869	.8865
45	.872	.880	.860	.8705	27 49	.8845	.8925	.872	.883
50	.885	.887	.8685	.880	30 22	.897	.899	.881	.8925
55	.879	.875	.8645	.873	32 43	.890	.887	.877	.8845
60	0.874	0.880	0.8715	0.8755	34 51	0.8825	0.890	0.8805	0.8845

R are "shrunk" to the left. The critical angle for the glass is the maximum that could ever be reached using glass plates.

Much greater difficulty was experienced in obtaining a good sodium mirror than in obtaining a potassium mirror, because of

TABLE II

Angle of Incidence	*O*		Angle of Incidence on Metal	*R*	
	Sodium	Rubidium		Sodium	Rubidium
13°5	0.8845	0.750	8°52′	0.895	0.756
15	.882	.757	9 50	.895	.764
20	.8825	.7575	13 3	.8935	.765
25	.8845	.7505	16 12	.8975	.758
30	.8785	.755	19 16	.8915	.7625
35	.8945	.755	22 14	.9075	.762
40	.8925	.7575	25 6	.905	.7645
45	.8975	.770	27 49	.910	.7775
50	.887	.7725	30 22	.899	.7775
55	.8975	.7705	32 43	.909	.776
60	0.900	0.775	34 51	0.9115	0.7755

the higher distillation point of sodium. Most of the attempts resulted in failures due to the formation of slight impure films on the metal next to the glass. These were probably oxide films,

as great care was always taken to clean the glass thoroughly. A mirror was, however, finally obtained which showed none of these films and appeared very perfect as viewed with the eye. The results are given in Table II.

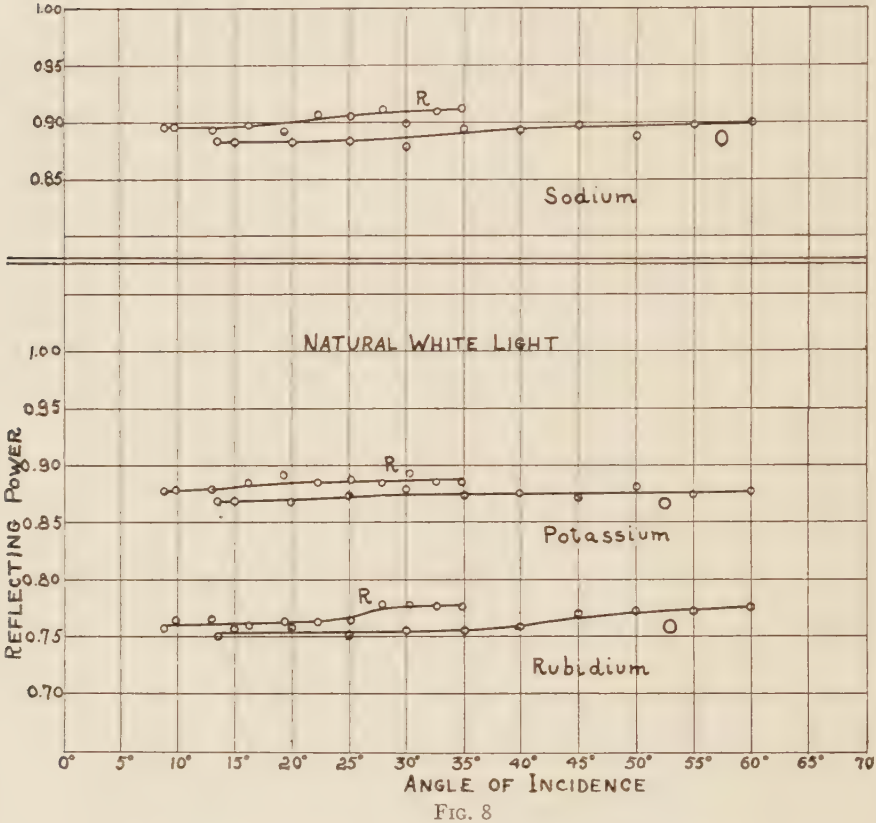

FIG. 8

No great difficulty was met with in the formation of rubidium mirrors, since the metal distills quite easily. The chief difficulty lies in obtaining the pure metal from its chloride. However, Rb is more easily oxidized than Na or K and hence a better vacuum must be insured. The values obtained with a mirror which showed no surface defects is given in Table II.

The values for Na are not plotted next to those for K in order to avoid confusion of contiguous points. In general, the reflecting

power rises slowly with the angle of incidence. The reflecting power is at first quite constant, then suffers a rather rapid rise, and then is nearly constant again. The values for the reflecting powers of the metals themselves are about 1 per cent higher than those for the whole mirror.

Na has the highest reflecting power, K being almost as good. Rb is less than K, so that the reflecting powers increase as the atomic weight decreases.

VIII. MONOCHROMATIC, POLARIZED LIGHT: ARRANGEMENTS OF APPARATUS

The source of light.—In this part of the work, it was proposed to investigate the reflecting powers of Na, K, and Rb for polarized

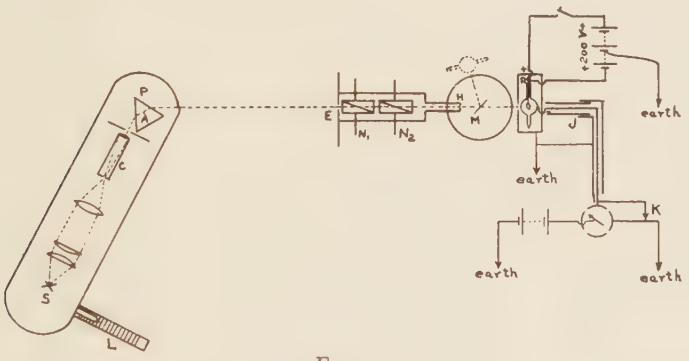

FIG. 9

monochromatic light. The arrangement of apparatus is shown in Fig. 9. In the case of white light, a Nernst glower was used as a source of light. Its use, however, was unsatisfactory, since it decreased so rapidly in efficiency owing to the polarization of the filament on direct current. The alternating current could not be used because it was too unsteady. Consequently for this part of the investigation, a 250-watt, nitrogen-filled, tungsten projection lamp was employed.

The optical system.—The light from one of the filaments *S* was focused upon the slit of the collimator *C*, after passing through the system of condensing lenses. The focal length of the collimator

was so adjusted that the emergent rays were just slightly convergent, the light being focused about 1.5 m away from the photo-electric cell. The central portion of the beam emerging from the collimating lens was allowed to pass through a good dispersing prism P, the spectrum being spread out over E. The source of light, condensing lenses, and prism were mounted on a movable table which could be rotated about an axis A through the center of the prism. Hence, by rotating this table any portion of the spectrum could be thrown upon the aperture E.

The light after passing through the rectangular nicols N_1 and N_2 and through the narrow slit H (7×1 mm), was incident directly upon the photo-electric cell, or else after reflection at the mirror M. The nicols served a double purpose, both for plane polarizing the light, and for calibration of the photo-electric current in terms of known light-intensities.

The photo-electric cell was used in connection with the spectrometer as in the previous work. The tube inclosing the nicols and containing the aperture H served to exclude extraneous light from the source. This tube was made purposely narrow toward the end in order to make the use of small angles of incidence possible when the photo-electric cell was swung around the spectrometer.

All light from extraneous sources was completely excluded by means of a double heavy cloth hung all around the apparatus, the room itself being partially darkened. That the screening was perfect was shown by the zero photo-electric current when the shutter of the cell was opened.

During observation upon the reflected light the nicols were arranged with their axes parallel to each other. The position of their planes of polarization was determined by the aid of a glass plate mounted so that the light was incident at the polarizing angle.

Calibration of apparatus in terms of wave-lengths.—The calibration of the scale L in terms of wave-lengths was effected by means of a Hilger wave-length spectrometer, the collimator of the instrument being placed in the position occupied by the photo-electric cell. It was found that the incident light was not purely monochromatic. A rapid test of the reflecting power of an alkali metal as a function of the wave-length showed this variation to

be very small. Hence it was unnecessary to procure purer monochromatic light.

The electrometer.—Since the light-intensities incident on the photo-electric cell are much smaller than in the case of white light, it was decided to use an electrometer to measure the photo-electric currents. The electrometer was of the Cambridge Scientific Co.'s type, giving a deflection of about 200 mm at a distance of 2.3 m for a difference of 1.5 volts between the two pairs of quadrants, there being 96 volts on the needle. The electrometer was placed in a fairly air-tight tin-box which was well earthed to a water-pipe.

One pair of quadrants was always left earthed; the other pair (which could also be earthed) was connected to the cathode of the photo-electric cell. The latter connection was effected through a wire which was completely protected from outside disturbing influences by being run through a glass tube, the outside of which was wrapped in tin-foil and well earthed. This protection for the wire was found to be absolutely necessary. A loose joint J permitted the motion of the photo-electric cell about the spectrometer.

The needle of the electrometer was carefully insulated by means of amber, so that under ordinary working conditions no leakage could be observed when the quadrants were charged to a difference of potential. There was, however, a slow drift in the direction of an increasing deflection, which proved quite troublesome. This seemed to be clearly due to a "dark current" or a leakage current across the glass of the photo-electric cell, notwithstanding the presence of the earthed ring between anode and cathode. However, by putting this ring at a potential of about 200 volts below that of the anode, the drift was completely eliminated.

The voltage employed across the cell varied from 80 to 120 volts, the negative pole of the battery being earthed as shown in Fig. 9.

IX. METHOD OF OBSERVATION

The electrometer was used "ballistically," i.e., the photo-electric cell was exposed to the light for a definite short interval, and either the resulting steady deflection or the "first throw" of the needle noted. The time interval was given by a metronome

adjusted to beat (approximately) seconds. The shutter in front of the photo-electric cell could be operated by the observer at his observing-post at the telescope. At the beat of the ticker, the shutter could be "snapped up" and then smartly closed at the end of the chosen time-interval. Proper weighting of the cord insured the smooth working of the shutter, and, after some practice, the time-length of exposure could be made to a tenth of a second.

Toward the latter part of this investigation, the humidity of the spring air made it difficult for the electrometer to hold its charge, so that instead of waiting for the needle to come to rest and noting the steady deflection the observer noted the first throw of the needle. It was found that not only was the accuracy of observation not marred by this procedure, but that, furthermore, double the number of observations could be taken in a given time-interval.

Light of a known mean wave-length polarized either parallel or perpendicular to the plane of incidence was allowed to fall on the shutter of the photo-electric cell. The electrometer key was opened, and, when the needle had come to rest, the cell was exposed to the light for 10 or 15 seconds, and the steady deflection or else the first throw noted. The deflections for the reflected light were alternated with those for the unreflected beam as previously. Deflections varying from 50 to 200 mm were employed.

In order to calibrate the observed deflections in terms of known light-intensities, keeping conditions the same as before the nicol N_1 was rotated through various angles, observations were taken in adjacent quadrants and the mean taken to correct for any asymmetry of the nicols with respect to the axis of rotation. These mean deflections were then plotted against the squares of the cosines of the angles. The light-intensities corresponding to the observed deflections for the reflected light could then be read on the curve, giving the reflecting powers directly. A calibration-curve was thus obtained for every series of observations.

The true relation between the light-intensity and photo-electric current can be determined only under the imposition of proper experimental conditions. In the present investigation, the interest lay not so much in the relation between the current and the light-

intensity, as in the relation between the light-intensity and resulting electrometer deflections. Experimental conditions were always employed such as to give greater stability and accuracy to the observations. Consequently as low a voltage as possible was used on the needle. Also, in part of the work, as previously mentioned, the first throw of the needle was employed. For these reasons, it is not safe to assume that the photo-electric current is proportional to the electrometer deflections. Hence the curves between electrometer deflections and light-intensity are not to be assumed as being relations between photo-electric current and light-intensity. They are merely to be regarded as calibration-curves. In general the curves approximated to straight lines, being either slightly convex or concave to the illumination-axis, depending upon the experimental conditions imposed. No theoretical value is assigned to these curves, consequently they are omitted. It must be remembered, however, that the curves given under white light are true current-light-intensity curves.

X. OPTICAL PROPERTIES OF THE GLASS PLATES

In the case of white light it was shown that the reflecting power of the metal itself is only slightly different from that of the mirror as a whole, the former being only from a fraction to a little over 1 per cent greater than the latter.

It has been shown that within experimental errors, Fresnel's reflection equations hold for the front face of the glass. Hence the values for r were calculated from the equations

$$r=\frac{\sin^2(i-\theta)}{\sin^2(i+\theta)} \text{ and } r=\frac{\tan^2(i-\theta)}{\tan^2(i+\theta)}$$

for light polarized parallel and perpendicular to the plane of incidence, respectively.

The variation of r with the wave-length is rather small (0.2 per cent over the range employed), since the variation in index of refraction is small, the range of wave-lengths extending from about 450 to 650 $\mu\mu$. The values of r for yellow light are plotted in Fig. 10.

The range of wave-lengths used being in the visible portion of the spectrum, it could be assumed a priori that the transmission

power of the glass for the different colors would be the same as for white light, since no dispersion or color-effects are ever visible to the eye upon looking through the glass. Nevertheless it was decided to test out this point by a short method.

Light polarized perpendicular to the plane of incidence was incident on the glass plate at the polarizing angle. Very little

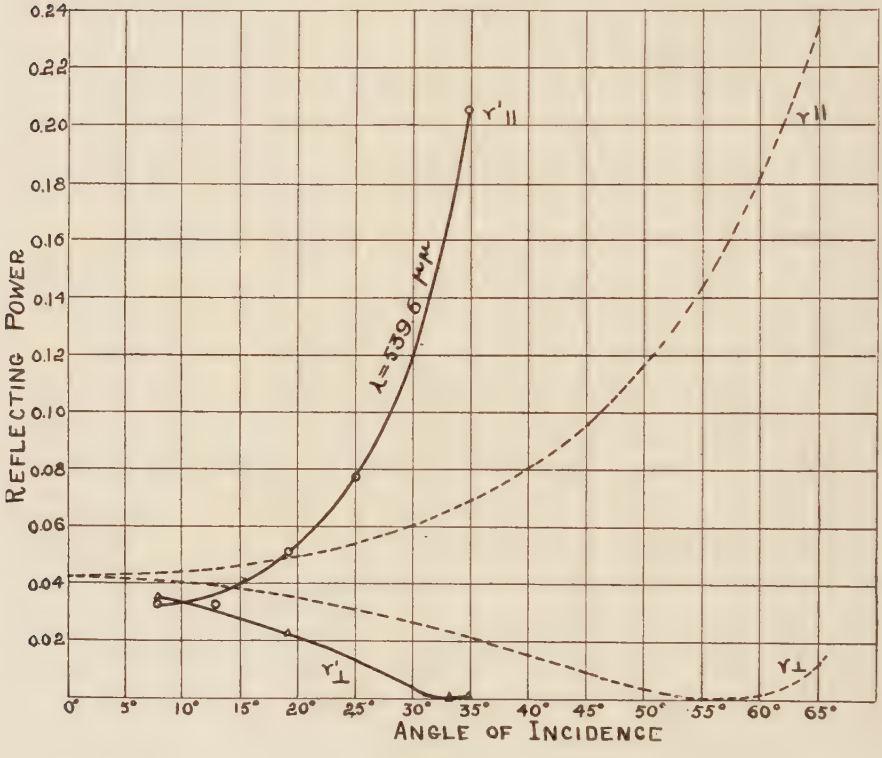

FIG. 10

light was thus reflected, practically all being transmitted. Hence the transmission power of the glass for that angle could be obtained by subtracting the transmitted from the incident light, allowing a small correction for the slight amount of reflected light.

Tests with various colors showed absence of any variation in the transmission power, the values for t being of the order given

in case of white light. As a result the values for t given in Fig. 7 were taken for this part of the work.

The values for r' (reflecting power of internal face of glass) for green light, taken for several angles of incidence, are shown in Fig. 10. These values for r' were used for all the colors. This use of r' is, however, not as radical as it might appear. In the first place, r varies very slowly with wave-length, hence the variation in r' must be likewise very small. Secondly, let us consider the equation for R in the form,

$$R = \frac{\frac{O}{I} - r}{t^2 \left\{ 1 - r'\left(1 - \frac{O}{I}\right) - r \right\}}.$$

The values of $\frac{O}{I}$ vary from 0.8 to 0.95. $1 - \frac{O}{I}$ is therefore a very small fraction, as well as r'. Consequently $r'\left(1 - \frac{O}{I}\right)$ is very small compared to $1 - r$, so that an error in r', even to the extreme extent of 5 per cent, could only result in an error of 0.1 or 0.2 per cent in the final value of R.

Inspection of the curves for r' shows that for small angles of incidence r' is less than r, but rises above r for angles of incidence approaching the critical angle at 41°. This rise is especially rapid in the case of light polarized parallel to the plane of incidence.

XI. RESULTS

The reflecting powers of potassium, sodium, and rubidium are given in the following tables and curves. The symbols $\parallel$ and $\perp$ on the curves indicate that the plane of polarization is parallel or perpendicular to the plane of incidence, respectively. In general, the reflecting powers are somewhat higher than those obtained for white, unpolarized light. The curves are similar to those obtained for a transparent medium, i.e., the reflecting power for light polarized parallel to the plane of incidence increases steadily with increased angle of incidence, while for light polarized perpendicular to the plane of incidence, the reflecting power decreases with increased angle of incidence. In the latter case the minimum value

reached would of course not be equal to zero as in the case, e.g., of glass.

The curves for K are not as smooth as those for Na and Rb owing to the fact that the steady deflection method was used in the case of K, while the method of first throw was used in the case of Na and Rb. Furthermore, nearly all of the points for Na and Rb are the mean of two values. Na has on the general average just

TABLE III

REFLECTING POWER (*O*) OF RB MIRROR NO. 2

Angle of Incidence	λ 640.9	λ 589.3	λ 539.6	λ 488.8	λ 454.6
PLANE OF POLARIZATION PARALLEL TO PLANE OF INCIDENCE					
12°	0.852	0.821	0.826	0.812	0.804
20	.844	.820	.820	.815	.805
25	.828	.828	.825	.824	.805
30	.870	.829	.820	.837	.809
40	.873	.845	.860	.833	.823
50	.875	.849	.828	.864	.845
60	.872	.868	.863	.875	.865
65	0.888	0.868	0.868	0.872	0.860
PLANE OF POLARIZATION PERPENDICULAR TO PLANE OF INCIDENCE					
12°	0.808	0.777	0.790	0.802	0.759
20	.813	.794	.793	.776	.753
25	.792	.788	.788	.783	.764
30	.822	.775	.800	.773	.748
40	.785	.769	.782	.770	.739
50	.797	.765	.760	.769	.750
60	.787	.762	.793	.780	.766
65	0.790	0.761	0.775	0.783	0.756

a slightly better reflecting power than K, Rb being less than either as for white light.

To the author's knowledge, no other investigation on Rb has ever been carried out, so that comparison is impossible. Great faith is, however, placed in the curves for Rb, since the results obtained for green light for two different mirrors check very well with each other (see Tables IV and V). The results of Tables III and IV are shown in Fig. 11. In these tables λ is given in $\mu\mu$.

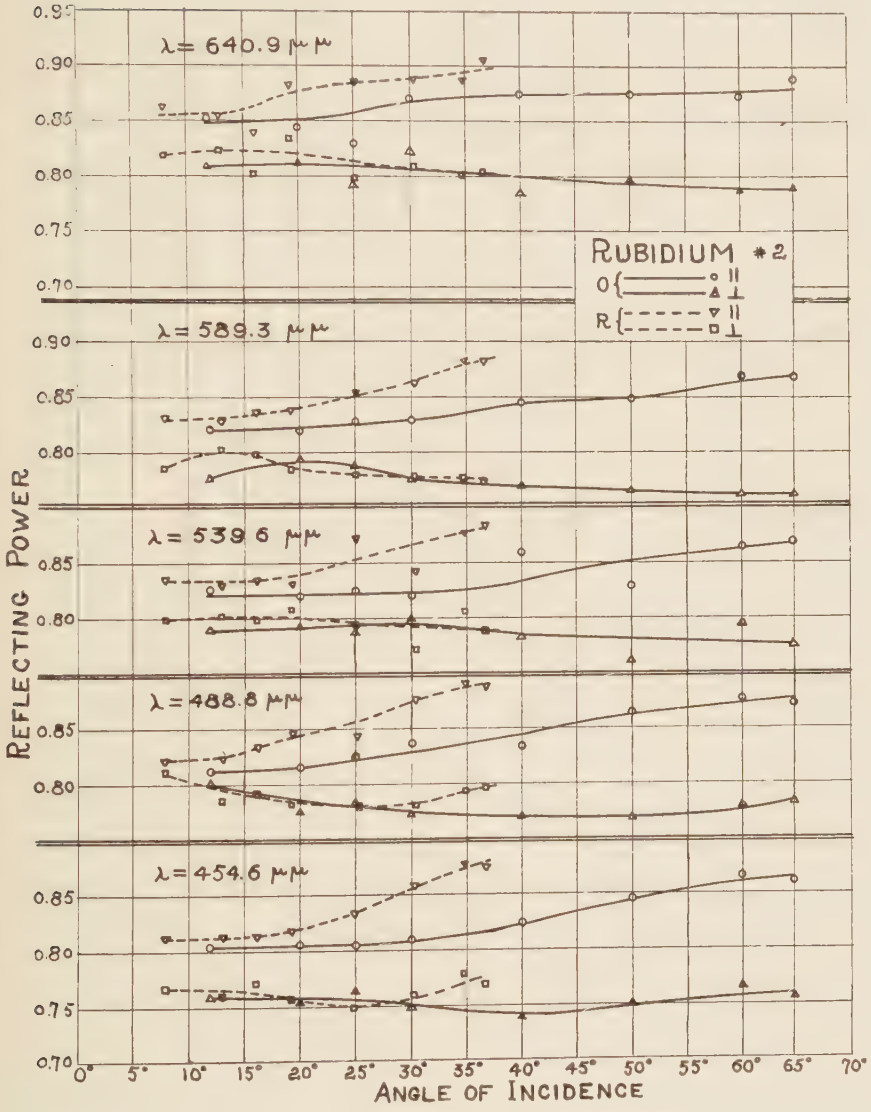
λ = 640.9 μμ
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
RUBIDIUM #2
O ∥
O ⊥
R ∥
R ⊥
REFLECTING POWER
ANGLE OF INCIDENCE
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65° 70°

FIG. 11

The results for Na and K are shown in Figs. 13 and 14.

The curves for Na for light polarized perpendicular to the plane of incidence are noteworthy. For small angles of incidence,

TABLE IV

REFLECTING POWER (R) OF RB NO. 2

PLANE OF POLARIZATION PARALLEL TO PLANE OF INCIDENCE

Angle of Inc.	λ 640.9	Angle of Inc.	λ 589.3	Angle of Inc.	λ 539.6	Angle of Inc.	λ 488.8	Angle of Inc.	λ 454.6
7°54′	0.862	7°53′	0.831	7°53′	0.835	7°52′	0.821	7°50′	0.812
13 4	.854	13 3	.829	13 2	.830	13 0	.824	12 58	.813
16 13	.838	16 12	.837	16 10	.835	16 8	.834	16 5	.813
19 18	.881	19 16	.838	19 14	.831	19 11	.847	19 8	.818
25 8	.885	25 6	.855	25 3	.872	25 0	.843	24 56	.833
30 25	.888	30 22	.863	30 18	.841	30 14	.875	30 9	.857
34 55	.887	34 51	.883	34 47	.877	34 42	.891	34 36	.878
36 48	0.904	36 44	0.882	36 39	0.884	36 34	0.888	36 27	0.874

PLANE OF POLARIZATION PERPENDICULAR TO PLANE OF INCIDENCE

7°54′	0.818	7°53′	0.785	7°53′	0.799	7°52′	0.811	7°50′	0.766
13 4	.823	13 3	.803	13 2	.802	13 0	.785	12 58	.760
16 13	.802	16 12	.798	16 10	.798	16 8	.792	16 5	.771
19 18	.833	19 16	.785	19 14	.810	19 11	.783	19 8	.756
25 8	.797	25 6	.780	25 3	.793	25 0	.780	24 56	.748
30 25	.809	30 22	.778	30 18	.771	30 14	.780	30 9	.760
34 55	.801	34 51	.776	34 47	.805	34 42	.794	34 36	.778
36 48	0.803	36 44	0.773	36 39	0.788	36 34	0.796	36 27	0.769

TABLE V

REFLECTING POWER FOR RB MIRROR NO 1

FOR $\lambda = 539.6$ $\mu\mu$

PLANE OF POLARIZATION PARALLEL TO PLANE OF INCIDENCE				PLANE OF POLARIZATION PERPENDICULAR TO PLANE OF INCIDENCE			
O		R		O		R	
Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6	Angle of Incidence	λ 539.6
12°	0.806	7°53′	0.814	12°	0.805	7°53′	0.815
20	.828	13 2	.837	20	.802	13 2	.812
25	.837	16 10	.847	25	.813	16 10	824
30	.838	19 14	.849	30	.808	19 14	818
40	.843	25 3	.854	40	.801	25 3	.812
50	.850	30 18	.862	50	.789	30 18	.801
60	.863	34 47	.877	60	.795	34 47	.808
65	0.861	36 39	0.877	65	0.785	36 39	0.798

the reflecting power first increases and then decreases. This appears to become more marked as the wave-length decreases. This is the only evidence that has been obtained that may throw light on the selective photo-electric effect as depending upon the optical properties of the metals.

The Rb curves also show similar evidence, though not so marked as in Na.

The reflecting powers are given with reference to glass as the adjacent medium. Were the metals in contact with a vacuum, the results would have been slightly higher. The magnitude of

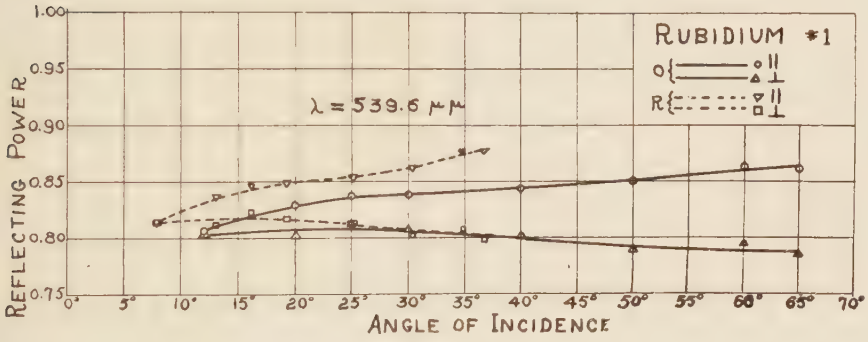

FIG. 12

this increase may be obtained as follows. Taking R. W. and R. C. Duncan's results for K for $\lambda = 589.3\ \mu\mu$, we have $n = 0.068$ and $\kappa = 22.1$. Hence, we obtain a value of 0.92 for the reflecting power of K by substituting in the formula for normal incidence, i.e.,

$$R = \frac{n^2(1+\kappa^2)+1-2n}{n^2(1+\kappa^2)+1+2n}.$$

It has been shown by Ingersoll[1] that the reflecting power of a metal in contact with a vacuum can be obtained from the reflecting power of the metal in contact with a medium of refractive index, m, by dividing n by m and substituting in the formula above for R. In our case, $m = 1.5155$, so that R would become in the case above, 0.914. The reflecting powers, as they are given in the

[1] *Physical Review*, **29**, 392, 1903.

tables and curves, would thus be a fraction of a percentage *higher* were the metal in contact with a vacuum instead of with glass.

XII. RELATION BETWEEN OPTICAL AND ELECTRICAL PROPERTIES OF METALS

Starting with Maxwell's electro-magnetic equations, it can be shown that, in the case of very good conductors like metals, the relation between the reflecting power, conductivity, and wave-length is given by

$$R = 1 - \frac{2}{\sqrt{\sigma c \lambda}} \qquad (8)$$

where σ is the electrical conductivity in c.g.s. electro-magnetic units, c is the velocity of light, and λ is the wave-length. This relation holds theoretically only for very long wave-lengths. Hence, as the wave-length λ increases, the second term diminishes, and R increases, becoming unity for $\lambda = \infty$.

The variation of R for the alkali metals as a function of λ is shown in Fig. 15. There is a distinct rise of the reflecting power with increasing wave-length, thus confirming theory. The points on the curves represent the mean of the reflecting powers for light polarized parallel and perpendicular to the plane of incidence, and for an angle of incidence of 12°. The mean therefore represents very closely the reflecting power at normal incidence, to which the equation (8) applies.

In Table VI are given the experimental values for the reflecting powers for normal incidence. The values of the reflecting powers as given by equation (8) have also been calculated and inclosed in this table.

Inspection of Table VI shows that the experimental values of the reflecting power of sodium is about 3 per cent less than that calculated by R. W. and R. C. Duncan from their katopric measurements. On the other hand, the values of potassium in this table seem to be somewhat larger than those of Duncan.

In general the theoretical values are lower than the experimental, though the agreement in the case of Rb is very close. The reflecting power of Rb is thus confirmed by Maxwell's equation

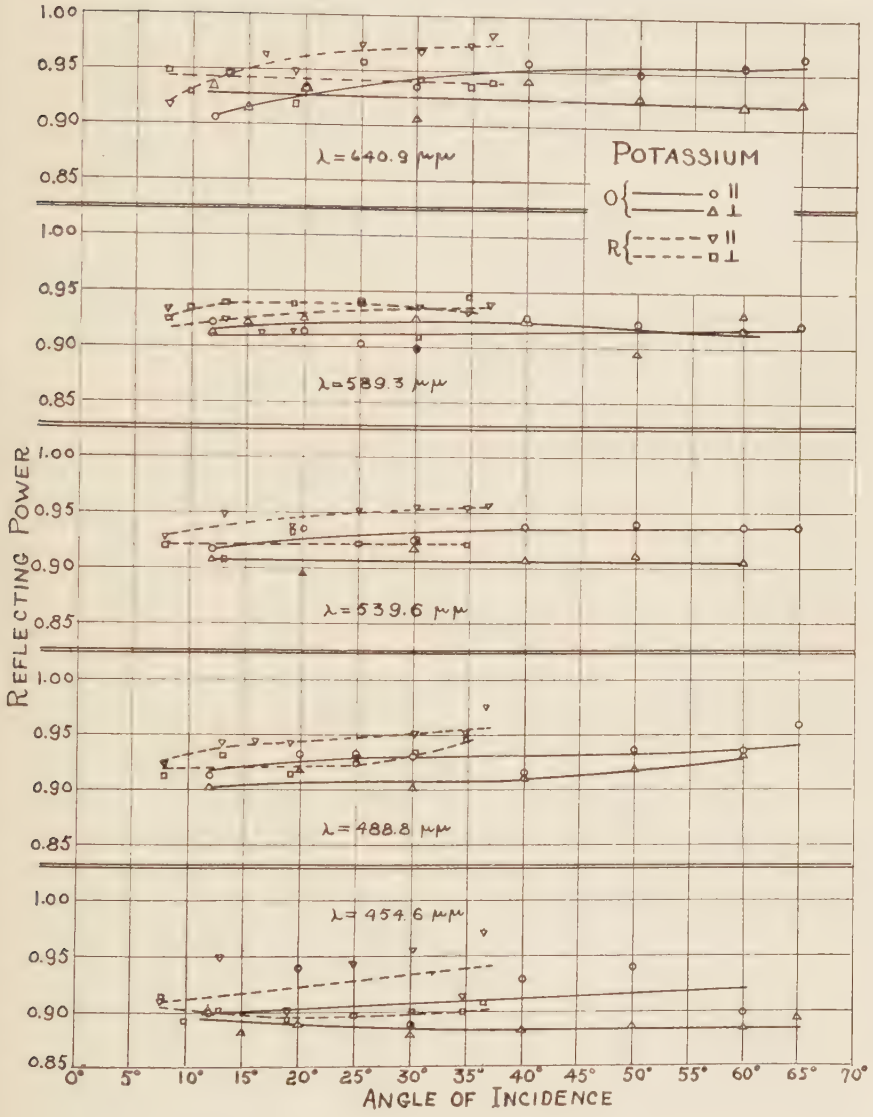
POTASSIUM
O { ——— ○ ∥
——— △ ⊥
R { - - - - - ▽ ∥
- - - - - □ ⊥
λ = 640.9 μμ
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
REFLECTING POWER
1.00
0.95
0.90
0.85
0° 5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65° 70°
ANGLE OF INCIDENCE

FIG. 13

of reflection. The discrepancy between theory and experiment becomes more marked if we put equation (8) in the form

$$\frac{(1-R)}{2}\sqrt{\sigma_{e.m.}\, c} = \frac{1}{\sqrt{\lambda}}. \qquad (9)$$

The value of the expression on the left-hand side of the equation appears to be only a function of the wave-length, and hence ought to be independent of the metal used. Calculations for $\lambda = 640.9\ \mu\mu$ made with Na, K, and Rb show, however, that the values of the left member of equation (9) are respectively 66.9, 69.3, and 117, while $\frac{1}{\sqrt{\lambda}} = 124.4$.

This discrepancy between theory and experiment shows that Maxwell's equations do not hold for the visible spectrum. In view

TABLE VI

NORMAL INCIDENCE

$\sigma_{e.m.}$ for Na $= \frac{1}{5072}$ e.m.u. (21°.7)
$\sigma_{e.m.}$ for K $= \frac{1}{7010}$ e.m.u. (20°.7) } Hornbeck[1]

$\sigma_{e.m.}$ for Rb $= 71 \times 10^{-6}$ e.m.u. (19°.3) Guntz and Broniewski[2]

WAVE-LENGTH $\mu\mu$	Na		K		Rb	
	Experimental	Theor.	Experimental	Theor.	Experimental	Theor.
640.9.....	0.945	0.897	0.933	0.879	0.840	0.829
589.3.....	.926	.893	.930	.874	.808	.822
539.6.....	.938	.888	.825	.968	.817	.814
488.8.....	.924	.882	.918	.861	.816	.804
454.6.....	0.914	0.878	0.912	0.857	0.789	0.797

of the modern electron theory this is not at all surprising, for Maxwell's theory does not take into account the effect of the resonating electrons within the metals upon the incident electromagnetic waves. That Maxwell's equation holds very well for

[1] *Physical Review* (2), **2**, 217, 1913.

[2] C. R., **147**, 1474, 1908; **148**, 204, 1909.

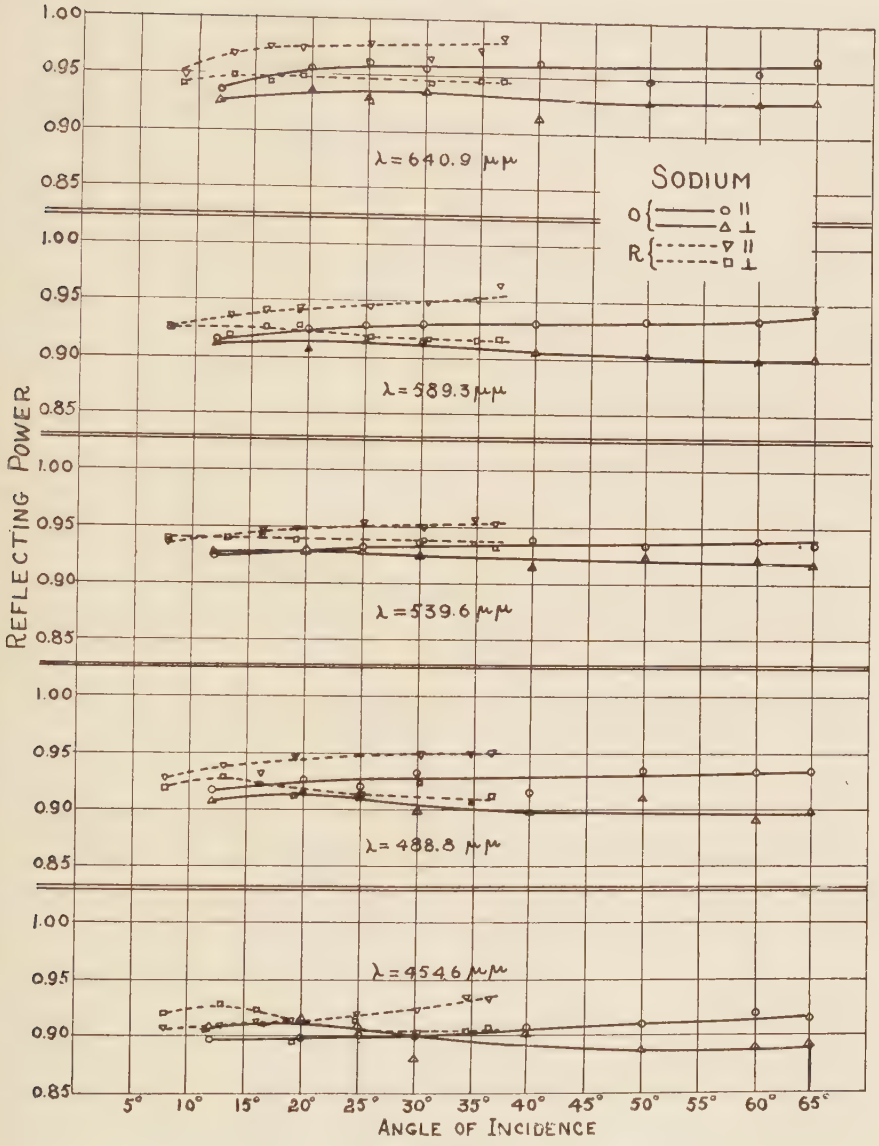
SODIUM
O { ——— ○ ||
——— △ ⊥
R { ------ ▽ ||
------ □ ⊥
λ = 640.9 μμ
λ = 589.3 μμ
λ = 539.6 μμ
λ = 488.8 μμ
λ = 454.6 μμ
REFLECTING POWER
1.00
0.95
0.90
0.85
5° 10° 15° 20° 25° 30° 35° 40° 45° 50° 55° 60° 65°
ANGLE OF INCIDENCE

FIG. 14

large wave-lengths was shown by Hagen and Rubens[1] for wave-lengths ranging from 8 to 15 μ.

Inspection of Fig. 15, for the case where the angle of incidence is 35°, shows that the reflecting powers of the alkali metals for light polarized perpendicular to the plane of incidence are always less than the reflecting powers for light polarized parallel to the plane

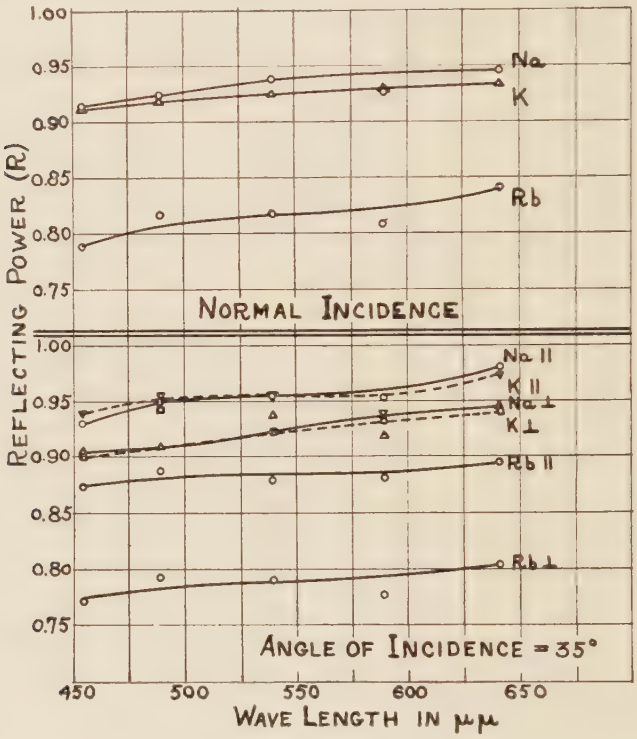

FIG. 15

of incidence. On the other hand, were the selective effect due to a change in the optical properties of the alkali metals, we should expect an abnormally high reflecting power for light polarized perpendicular to the plane of incidence. The range of wave-lengths employed in this investigation covers about one-half the

[1] *Annalen der Physik*, 11, 873, 1903.

selective region for potassium and about two-thirds that for rubidium. It therefore appears that the selective effect cannot be due to an abnormally high reflecting power in the region of the selective effect. This investigation must, however, be carried down to still smaller wave-lengths before the problem can be more definitely decided.

SUMMARY

1. The reflecting powers of sodium, potassium, and rubidium were determined for various angles of incidence, using white unpolarized light and also monochromatic light polarized parallel and perpendicular to the plane of incidence.

2. A rubidium-argon photo-electric cell was used as a photometer. It was calibrated in terms of known light-intensities by means of crossed nicols. The photo-electric current was found not to be strictly proportional to the light-intensity.

3. The alkali metals were used in the form of mirrors, which were made by distilling or pouring the metal on a glass plate forming a part of an evacuated cell.

4. Owing to reflection at the front and internal faces of the glass plate, the optical properties of the glass plate were determined in order to calculate the reflecting power of the metal itself. Fresnel's reflection equations for glass were verified.

5. The reflecting powers of Na, K, and Rb were found to decrease in the order named, i.e., as their atomic weights increased. The values for monochromatic light were found to be somewhat higher than those for white light. The results for Rb were found to be confirmed by Maxwell's equation for metallic reflection.

6. In the case of monochromatic polarized light, the reflecting power increased with increased angle of incidence for light polarized parallel to the plane of incidence, but decreased somewhat for light polarized perpendicular to the plane of incidence for the range of angles used.

7. The reflecting powers increased with increase of wave-length in accordance with Maxwell's theory.

8. The selective photo-electric effect does not seem to be due to any marked change in the reflecting powers of the alkali metals for light polarized perpendicular to the plane of incidence.

In conclusion, I wish to take this opportunity of expressing my thanks to Professor A. P. Carman for having so kindly placed the necessary facilities for research at my disposal, and to acknowledge my indebtedness to Professor Jakob Kunz for having suggested this problem, and for his many valuable and kind suggestions throughout this investigation.

Laboratory of Physics
University of Illinois
May 1916

VITA

Jonas Bernard Nathanson was born in Vilna, Russia, on September 5, 1889. He received his early education in the public schools of Toledo, Ohio, graduating from the Toledo Central High School in 1908. He entered the Ohio State University in the fall of 1908, and received the A.B. degree from this institution in 1912. During 1912–13 he was a graduate scholar in physics at the University of Illinois, receiving the A.M. degree from this institution in 1913. From 1913 to 1916 he was assistant in the physics department of the University of Illinois. He has published the following papers: "A Determination of e/m and v by the Measurement of a Helix of Wehnelt Cathode Rays," *Physical Review*, **2**, 307, 1913; "The Reflecting Power of Alkali Metals in Contact with Glass, as Determined by the Photo-electric Cell" (abstract), *Physical Review*, **7**, 403, 1916.